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Water inlet subcooling effects on flooding with steam and water in a large diameter vertical tube

W. Cullum[a,1], J. Reid[b], K. Vierow[a,*]

[a] Department of Nuclear Engineering, Texas A&M University, 337 Zachry Engineering Center, 3133 TAMU, College Station, TX 77843-3133, USA
[b] Department of Mechanical Engineering, Texas A&M University, 200 MEOB, 3123 TAMU, College Station, TX 77843-3123, USA

HIGHLIGHTS

- Flooding experiments were conducted using steam and water in a large-diameter tube.
- The effects of water subcooling were studied during the experiment.
- Tests were conducted at a variety of water flow rates and temperatures.
- The data confirmed use of a correlation to account for water subcooling.

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ABSTRACT

A counter current annular flow experiment was performed to determine flooding conditions for varying degrees of subcooling using steam and water. The findings can be used in reactor safety codes to provide an improved model of flooding during accident analysis. The test section is a stainless steel tube which is approximately a 5/16 scale version of a pressurized water reactor (PWR) surge line. The water flows in an annular film down the inside of the tube and steam flows upward through the annulus. Flooding is the point at which the water film reverses direction and begins to travel upward. Flooding tests were conducted at atmospheric pressure for water flow rates between 0.0132 m^3/min and 0.0416 m^3/min and water inlet temperatures between 308 K and 370 K. The data obtained at high water subcooling indicate a significant departure from accepted flooding correlations developed for air–water systems which is expected because vapor condensation alters the steam inlet flow rate needed to induce flooding. The data more closely follow air–water data at low subcooling. Such data has not been seen in the literature for steam–water flooding experiments in a large diameter vertical tube and will serve as an important benchmark.

1. Motivation for this research

In reactor accident analysis, flooding is an important phenomenon which can preclude accident mitigation and, in certain circumstances, compound the accident. Flooding occurs in two-phase annular flow regimes where the liquid is in an annular film on the inner surface of the pipe, surrounding upward flow of the gaseous core. Flooding is defined as the partial or complete reversal of the liquid film flow direction. Another term for flooding is called the counter-current flow limitation (CCFL) or the transition from counter-current flow to co-current flow. This phenomenon is not specific to nuclear power plants and can be found in many engineering applications. Due to its broad existence, flooding has been studied for many decades in different forms.

This research pertains to a postulated flooding scenario in nuclear power plants. In a pressurized water reactor (PWR), the reactor coolant system pressure is maintained by a component called the pressurizer. The pressurizer is connected to the hot leg of the main coolant system via the pressurizer surge line. In hypothetical reactor accidents such as a station blackout, the ability to remove heat from the reactor core could be lost. This results in the generation of steam within the reactor coolant piping. As coolant is discharged through the cycling relief valve at the top of the pressurizer, the chance of flooding in the pressurizer surge line intensifies. If flooding occurs in the pressurizer surge line, the wall temperature of the pressurizer surge line can increase sharply to the steam temperature in the vapor core. This is due to a breakdown of the

* Corresponding author. Tel.: +1 979 458 0600; fax: +1 979 845 6443.
E-mail address: vierow@tamu.edu (K. Vierow).
1 Tel.: +1 979 458 0600; fax: +1 979 845 6443.

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annular film which causes local dryout conditions within the pipe. If flooding occurs for an extended period of time, the pressurizer surge line could rupture due to plastic deformation caused by high temperature creep.

The objective of this research is to study the effects of the subcooling of inlet water on the occurrence of flooding. In order to produce the necessary data, numerous flooding tests were conducted at differing degrees of water subcooling. First, the maximum degree of subcooling achievable while still allowing the flooding phenomenon was identified. Then, flooding tests were performed in increments of 5 K subcooling until the water inlet temperature reached the saturation temperature or until a limitation of the experimental facility was reached. After all of the flooding tests were performed, the data was compared to previous data obtained at similar conditions to validate the current data. The data were then analyzed for consistency using correlations already developed for flooding. Discrepancies between existing correlations and the current data were discussed and, recommendations were given on correlations used to account for the water subcooling effects in flooding.

Several important outcomes will be the results of this flooding research. Primarily, a correlation has been developed and will be validated to account for the water subcooling effects on flooding using steam and water. This correlation can be used in reactor accident computer codes to better predict conditions within the pressurizer surge line in severe accidents such as a station blackout or loss of coolant accident. Additionally, more data will be added to flooding database so that a more complete model of flooding may be produced instead of facility-specific correlations. As future researchers continue to analyze the counter-current flow limitation, aspects of flooding can be generalized to form one complete model. Lastly, an important benchmark has been achieved by comparing low subcooling steam–water flooding data to air–water data. This comparison has not been performed in previous research and is providing an important benchmark for validation of the current research.

2. Previous research

Counter-current flow limitation is a phenomenon which has been studied in various forms for many years. Numerous fluids and gases have been studied along with various inlet and outlet geometries. For the purpose of this research, many of these experiments can be disregarded as they do not pertain to the direct concentration of this experiment. However, some important past work influential to this endeavor will be examined to provide the essential framework. This previous work does not necessarily deal solely with steam/water flooding, nonetheless each provide significant insight into the phenomenon.

2.1. Wallis correlation

Flooding was first investigated in the use of packed towers to separate waste products from gases. In packed towers, scrubbing liquid flows down through the packed tower as gas flows upward. As the gas passes through the liquid, the waste products are stripped out of the gas leaving clean gas at the outlet of the tower. The limiting velocity of the gas is the point at which flooding occurs and the liquid reverses direction which was studied by Sherwood and Lobo (Sherwood et al., 1938; Lobo et al., 1946). Some of the initial studies were performed by G.B. Wallis who researched and developed correlations primarily for air and water experiments although he performed some studies with steam and water as well (Wallis et al., 1980). The parameters used in studying flooding phenomena are the liquid and gas superficial velocities.

$$j_f^* = \frac{\rho_f^{1/2} j_f}{[gD(\rho_f - \rho_g)]^{1/2}} \tag{1}$$

$$j_g^* = \frac{\rho_g^{1/2} j_g}{[gD(\rho_f - \rho_g)]^{1/2}} \tag{2}$$

Wallis first performed experiments using air and water in which he developed the correlation known as the Wallis correlation.

$$j_g^{*1/2} + m j_{f,d}^{*1/2} = C \tag{3}$$

The constants m and C in Eq. (3) are constants determined by the geometry of the experimental setup. The constants are influenced by the test section diameter as well as the entrance and exit arrangements of the test section. Small changes in the design of the experiment can generate substantial differences in these constants. Wallis considered the entrance and exit of different facilities to either be sharp or smooth. The parameter $j_{f,d}$ in Eq. (3) is the liquid superficial velocity that flows in the downward direction during flooding (Wallis, 1969, 1961).

The Wallis correlation has provided a baseline for flooding experimentation, yet it has limitations. Specifically, it is only valid for small diameter tubes and experiments using air and water since he developed the correlation with data solely from experiments using air and water.

2.2. Kutateladze numbers

After the initial development of the Wallis correlation, Pushinka and Sorokin studied the occurrence of film breakdown, or a complete reversal of the liquid film, in vertical tubes of varying sizes. In the performance of this experiment they used the dimensionless numbers developed by Kutateladze to compare to the Wallis correlation. The Kutateladze numbers were developed during a hydrodynamic study to determine if bubble formation during boiling and bubbling were similar (Kutateladze and Malenkov, 1966; Kutateladze, 1961, 1972). As such, the Kutateladze number includes the same buoyancy and fluid friction forces as the volumetric flux used in the Wallis correlation while also taking into account the surface tension effects produced by the bubble.

$$K_f = \frac{\rho_f^{1/2} j_f}{[g\sigma(\rho_f - \rho_g)]^{1/4}} \tag{4}$$

$$K_g = \frac{\rho_g^{1/2} j_g}{[g\sigma(\rho_f - \rho_g)]^{1/4}} \tag{5}$$

Pushinka and Sorokin observed that for the large diameter tubes used in the experiment, the tube diameter does not have an impact on the magnitude of air velocity required to breakdown the film. Therefore, the data they obtained by using the Kutateladze numbers did not agree with the Wallis correlation since the Wallis correlation predicts that the tube diameter has a significant impact on the air velocity required to induce flooding (Pushinka and Sorokin, 1969).

The threshold for declaring a tube large or small has also been studied by several researchers. The most widely accepted method for determining this threshold is to use the critical Kutateladze value of 3.2. This also correlates with the better known bond number of 30 or greater. Vijayan et al. performed research to determine the diameter effects of tubes of differing sizes on flooding. Upon the conclusion of his experiment, he found that tubes greater than 67 mm in diameter can be considered large and the Kutateladze number can be used to accurately quantify results (Vijayan et al.,